# Geology of the Salt Lake Area, Oahu, Hawaii[1]

KOST A. PANKIWSKYJ[2]

ABSTRACT: A series of pyroclastic eruptions and one lava flow, all of melilite-nephelinite composition, were produced in the environs of present-day Salt Lake, Oahu, Hawaii, beginning about 500,000 years ago and terminating more than 100,000 years ago. The age of the flow has been dated by a $K_{40}/A_{40}$ method at 400,000 years to 470,000 years. The earliest eruptions took place at a time of higher sea levels than at present, and their products are water-laid. Later eruptions, including the major ones from Salt Lake Crater and Makalapa Crater, took place at a time of lower sea levels than at present, and their products are air-laid. Sufficient time elapsed between individual eruptions to allow for erosion of portions of the earlier cones, to deposit silt and gravel, or to develop a soil prior to a subsequent eruption. The pyroclastics are medium- to fine-grained, lithic-vitric tuffs and contain, in addition to juvenile material, a considerable quantity of particles of older rocks—volcanic and sedimentary, as well as ultramafic. The youngest deposits of tuff are unconformably truncated by reef and limestone which have been correlated with rocks dated by a $Th_{230}/U_{238}$ method at 90,000 to 140,000 years.

THE PYROCLASTICS of the Salt Lake area of Oahu, Hawaii have a long history of geologic investigation. Hitchcock (1900), Wentworth (1926), and Stearns and Vaksvik (1935) comprise the most notable stratigraphic studies. New cuts were made in the early 1950s along the widened Moanalua Highway north of Salt Lake and, in the late 1960s, on the inner slopes of Salt Lake during development of a residential subdivision. This investigation was undertaken in order to examine new exposures as they were being developed and before they became covered by man-made structures or were permanently removed in the process of earth-moving. The aim of the investigation was to establish a detailed stratigraphy and geologic history of the pyroclastic section in the Salt Lake area.

*Summary of Geologic History*

The extinction of the Tertiary Koolau shield volcano, which built the eastern part of the island of Oahu, was followed by a period, probably in excess of 1 million years, of weathering and erosion. About one-half million years ago, the topography in the present Salt Lake area consisted of stream-cut valleys filled with silts and gravels, separated by ridges of erosional remnants of Koolau lavas which were covered in places by red or brownish red soil. The initial deposits of Pleistocene pyroclastic material in the Salt Lake area are water-laid and are intercalated with the silts and gravels noted above. The water-reworked cinder has been attributed to Aliamanu Crater (Stearns and Vaksvik, 1935, p. 109). More than one horizon of pyroclastics is mapped, attesting to either a number of separate eruptions or else removal and reworking of ash from one major eruption. Land vegetation came to cover the entire Pearl Harbor–Salt Lake area following a lowering of the level of the sea. At this time eruptions from several craters in the Salt Lake area formed subaerial cones of tephra. Those which I was able to recognize are shown in Fig. 1, and are referred to in this paper as: Aliamanu School Cone, Moanalua Cone, Akulikuli Vent, and the Wiliki Cone. These cones were subject to erosion prior to being mantled by the major, most voluminous eruptions of air-laid tuff from Salt Lake Crater, which, together with tuff erupted contemporaneously from Makalapa Crater, covers approximately 12 square miles at the present time. The

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[2] University of Hawaii, Department of Geology and Geophysics, Honolulu, Hawaii 96822.

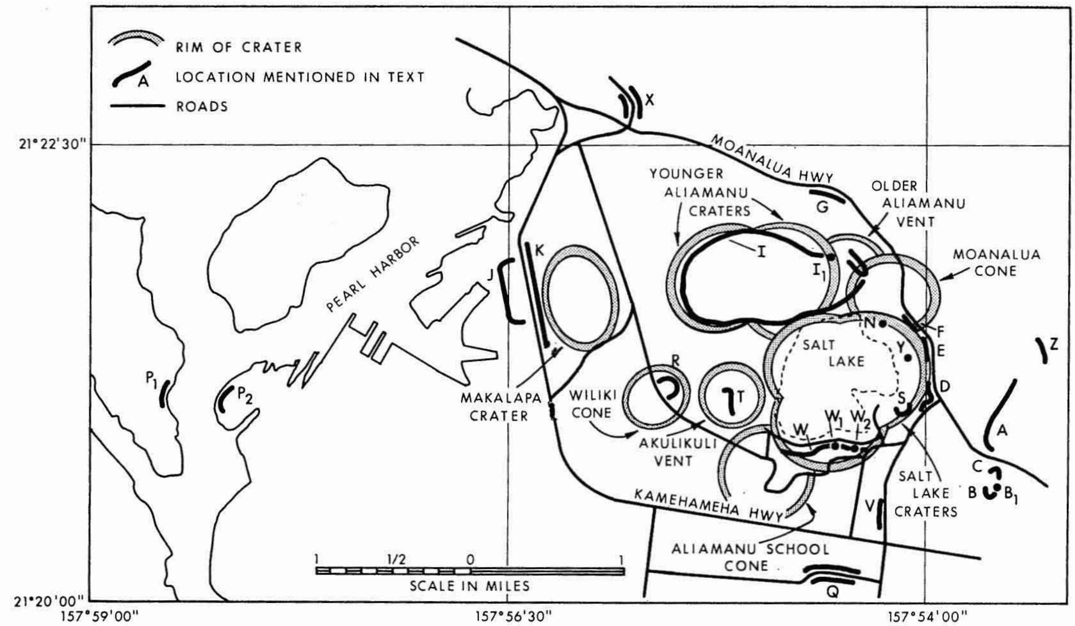



FIG. 1

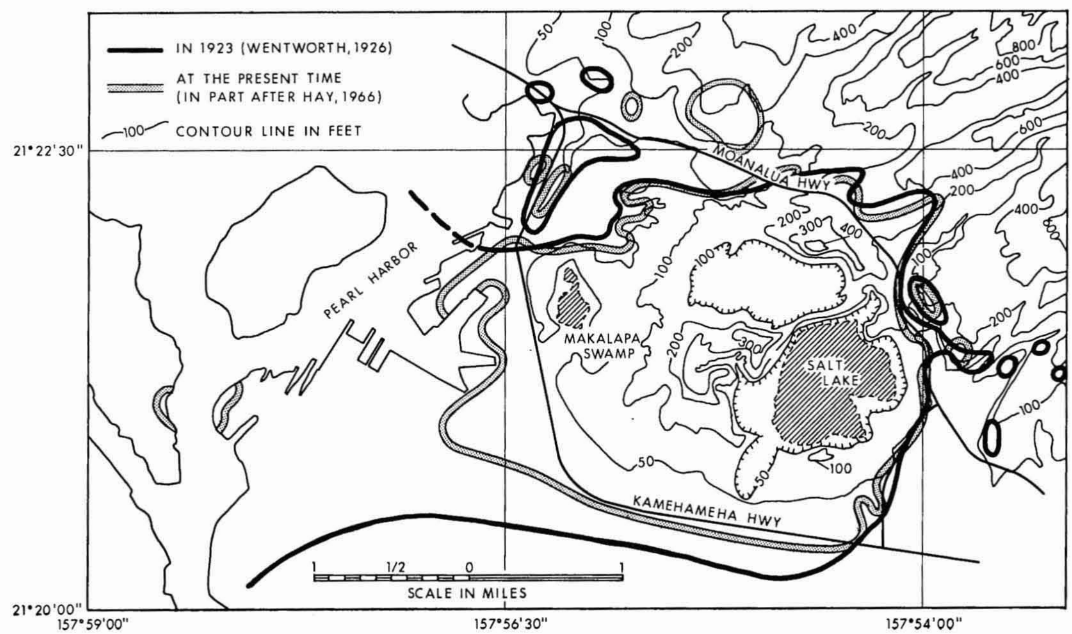



FIG. 2

extent of surface exposure of air-laid tuff from these eruptions is shown in Fig. 2.

On the seaward sides of the craters deposits of this tuff are capped by reef, testifying to a gradual rise in the level of the sea. Stearns (Stearns and Vaksvik, 1935, p. 127–128) related the high, low, and final high sea levels to the Kaena, the Waipio, and the Waimanalo stands, respectively.

*Summary of Stratigraphy*

The stratigraphic section in the Salt Lake area is divided into four groups for the purpose of ease of discussion and comparison:

Group 1. Tertiary rocks of the Koolau Volcanic Series and their weathering products, which are typically highly oxidized red-colored soils showing little if any stratification.

Group 2. Water-laid, valley-filling sequences of well-stratified reddish, brownish, and buff silts and clays; beds and lenses of gravel; reworked cinder of the Honolulu Volcanic Series; air-laid tuff from the several small cones which were formed prior to the major eruption from the Salt Lake and Makalapa craters; and various lagoonal and littoral sediments including calcareous sandstone and siltstone, lime muds, coral, and shelly reef fragments, some of which are intercalated with fine volcanic ash.

Group 3. Typically air-laid tuff from the Salt Lake and Makalapa craters including the youngest pyroclastic deposit, a poorly consolidated dark grey ash.

Group 4. Calcareous deposits overlying the Group 3 tephra.

*Description of Individual Cuts*

Eruptions from the crater, or more likely from several craters, in what subsequently developed into Salt Lake, completely blanketed the deposits of earlier eruptions. Some of the earlier deposits became uncovered by erosion, but most remained unexposed until excavated by man in the 20th century. It is to be expected that, in addition to the craters described in this paper, others may still be identified with further excavation.

The first geologic description of the Salt Lake craters is by J. D. Dana (1849, p. 245–248), who was the geologist of the 1838–1842 U.S. exploring expedition under the command of Charles Wilkes, U.S. Navy. He describes the topography of the area and recognizes the three craters of Salt Lake, Aliamanu, and Makalapa. Hitchcock (1900) describes the Salt Lake region in more detail and notes particularly a cut along the Oahu Railroad less than one-half mile west of Moanalua Station (near the present intersection of Puuloa Road and Kamehameha Highway?), which from bottom to top consisted of: "the main coral reef; thin layer of tuff; coral reef or limestone; decomposed rock sustaining a soil covered by forest; eruption of tuff from Aliapakai [Salt Lake Crater] . . ." This exposure is no longer in existence. Wentworth (1926) specifically separates the typically water-laid tuff below the air-laid tuff and discusses in detail the geologic history of the area. The most recent comprehensive description of the stratigraphic sections in the area is by Stearns and Vaksvik (1935). I will call on their descriptions from place to place in the discussion which follows.

Stearns (Stearns and Vaksvik, 1935, p. 105) describes in considerable detail a cut on a private road to the Damon Estate leading up a bluff on the southeast side of Manaiki Stream about 1,500 feet northwest of the main entrance to Fort Shafter (the present-day Pineapple Street?). This location is shown as *A* on Fig. 1, and the description of the section is shown at *A* in Fig. 3. Today, this exposure is heavily covered with vegetation along its slope and by houses on top. The best present exposure in this vicinity is along the loop of road from Moanalua Highway to the seaward part of Fort Shafter, shown as locations *B* and *C* on Fig. 1, *B* being seaward of *C*.

These sections are shown in Fig. 3. They consist entirely of the Group 2 of this report and can be divided into three parts. In decreasing age these are:

Part 1. Roughly bedded, rounded, water-laid dark grey cinder interlayered with a light brown silt and several boulder lenses. This grades laterally toward the south into interlayered silt and gravels.

Part 2. A 2- to 3-inch layer of tuffaceous mud containing numerous plant fragments, well-rounded cobbles and boulders of Koolau lithology in a tuffaceous matrix, and a well-bedded water-laid tuff.

Part 3. Light brown silt with several lenses of gravel. In the southern part of cut *B* also appears a bed of lithified calcareous sandstone containing fragments of reworked tuff and cinder.

A section equivalent to the Part 1 above also appears to be present near the top of the bluff on the east side of Moanalua Gardens, the section *A* taken from Stearns. He described it as a "stratified water-laid pumiceous fire-fountain deposit." A similar section is also seen at the present time just southeast of the crossing of Mahamoe Street over Manaiki Stream, location *Z* on Fig. 1, where it is seen to grade downward into a buff soil, and yet farther down into spheroidally weathering aa flows of the Koolau Series.

The imposing bluff at the corner of Moanalua Highway and Puuloa Road consists of a section of Group 2, very similar to that at Fort Shafter, but for the presence of the Salt Lake Tuff, Group 3 of this report, capping the Group 2 section.

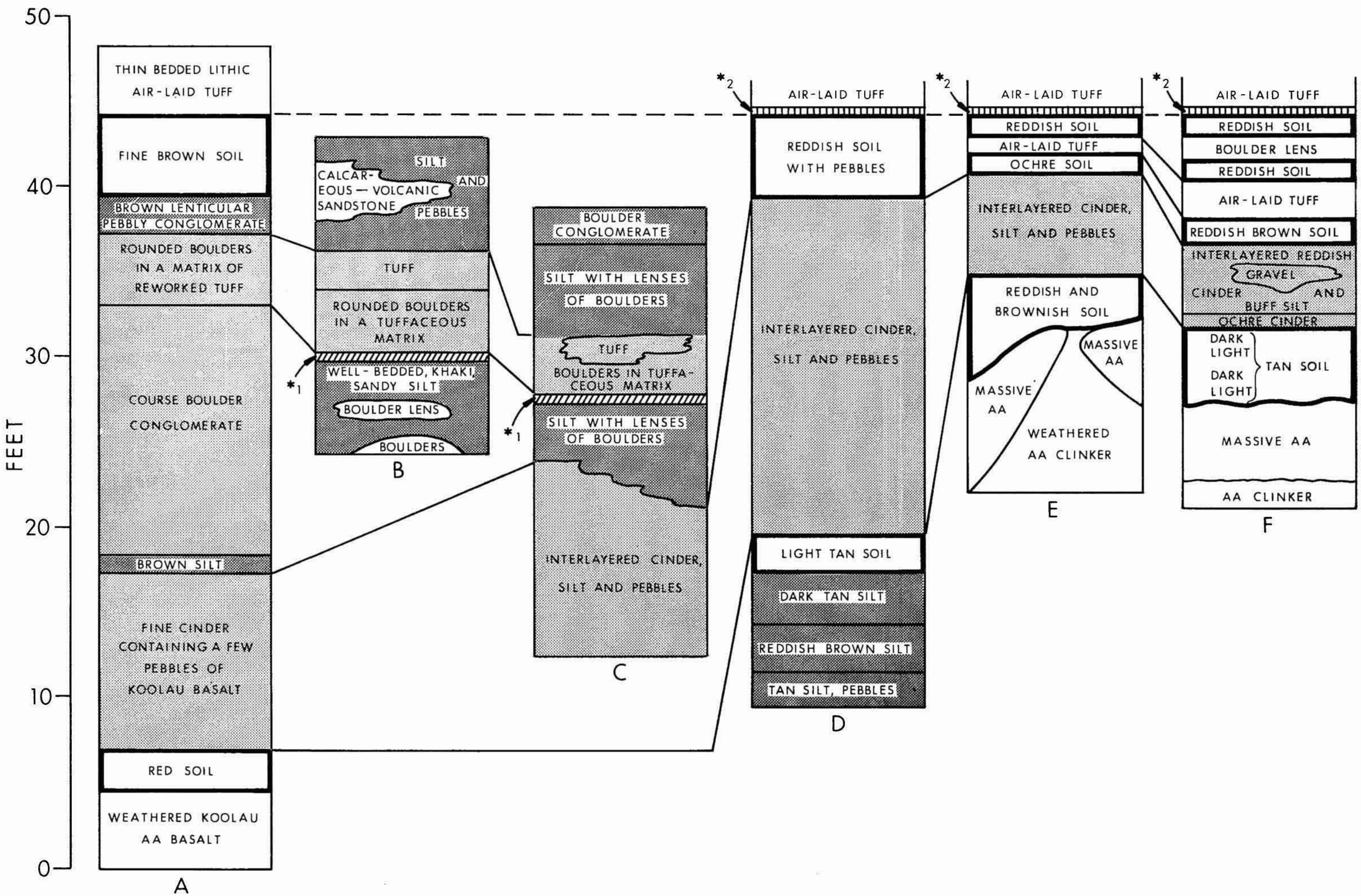
As one traverses Moanalua Highway from the corner of Puuloa Road toward the northwest, the following section can be observed in three successive cuts on the southwestern side of the highway, located on Fig. 1 as *D, E,* and *F,* respectively.

At the base of cuts *E* and *F* is found a Group 1 section, the eroded remnants of Koolau lavas, covered by a reddish or brownish soil layer. Then in all three cuts are found sections composed of sediments of Group 2. The silts are thickest in cut *D,* which is a section through a fluvial flood plain. The gravels are coarsest in cut *F,* which lies near the center line of the ancient Moanalua River Valley. These gravels form lenses within interlayered water-laid cinder and brownish silt, equivalent to part 1 of the Fort Shafter cut (*B* and *C* in Fig. 3). Above this follow more silts and gravels, but also a 2- to 3-foot layer of tuff containing plant remains. This is then capped by the Salt Lake Tuff, the Group 3 section. The lower contact of the Salt Lake Tuff is at the present time particularly well displayed on an excavated hill sloping south toward Salt Lake directly west of the northwestern entrance to the Henry Damon Estate, located at *N* on Fig. 1. At the bottom of this section, with its base not exposed, is a 5-foot thickness of a very poorly sorted, very roughly bedded tuff, overlain by brown silt with lenses of coarse gravel, those in turn overlain by a dark grey, but deeply red-weathering soil which, near the top, contains well-preserved plant remains. Above this is the base of the Salt Lake Tuff, characterized by a 2- to 6-inch-thick layer of light grey poorly consolidated fine-grained tuff, rich in fossil plant remains. Above this follows well-consolidated air-laid tuff. The roughly bedded tuff underlying the soils and gravels is considered to be a remnant of a minor tuff cone, here referred to as the Moanalua Cone which erupted on the floor of the pre-Salt-Lake Moanalua Valley. It is this cone, in my opinion, that first dammed Moanalua Stream and diverted its course to the southeast.

Within the Salt Lake Crater area, on the northeast side of Ala Puumalu just southeast of Ala Napunani (location *Y* on Fig. 1), one can at this time still find a similar section of poorly consolidated cinder, covered by brown to red soil, which, in turn, is covered by a very poorly sorted tuff containng numerous xenoliths of Koolau lava.

Farther westward along Moanalua Highway, the base of the Sale Lake Tuff dips below the level of the highway until the highway reaches the crest of Red Hill and then drops into Halawa Valley, shown as location *G* in Fig. 1. At the crest of the hill a weathered aa flow is capped by only a few inches of red soil, and this is capped by air-laid tuff. Partway down the slope to Halawa Valley the soil is thicker and one can see the section illustrated at *G* in Fig. 3.

Lower in Halawa Valley, beds of coarse gravels are found intercalated with the soils below the Salt Lake Tuff. Stearns (Stearns and Vaksvik, 1935, p. 110) reported a similar section at the former Aiea Station of the Oahu Railroad. This description is shown as *H* in Fig. 3. I have not located this exposure; however, a recent cut along the H-1 expressway southeast of Aiea, shown as location *X* on Fig. 1, shows a similar stratigraphic section, with the exception that the subaerial tuff attributed to Salt Lake-Makalapa craters is not present, possibly having been removed during excavation, and the horizontally bedded gravel and silt is seen to grade downward into a brownish red soil,


50
40
30
20
10
0
FEET
THIN BEDDED LITHIC AIR-LAID TUFF
FINE BROWN SOIL
BROWN LENTICULAR PEBBLY CONGLOMERATE
ROUNDED BOULDERS IN A MATRIX OF REWORKED TUFF
COURSE BOULDER CONGLOMERATE
BROWN SILT
FINE CINDER CONTAINING A FEW PEBBLES OF KOOLAU BASALT
RED SOIL
WEATHERED KOOLAU AA BASALT
A
SILT
CALCAR-EOUS — VOLCANIC SANDSTONE
AND
PEBBLES
TUFF
ROUNDED BOULDERS IN A TUFFACEOUS MATRIX
*1
WELL-BEDDED, KHAKI, SANDY SILT
BOULDER LENS
BOULDERS
B
BOULDER CONGLOMERATE
SILT WITH LENSES OF BOULDERS
TUFF
BOULDERS IN TUFFA-CEOUS MATRIX
*1
SILT WITH LENSES OF BOULDERS
INTERLAYERED CINDER, SILT AND PEBBLES
C
*2
AIR-LAID TUFF
REDDISH SOIL WITH PEBBLES
INTERLAYERED CINDER, SILT AND PEBBLES
LIGHT TAN SOIL
DARK TAN SILT
REDDISH BROWN SILT
TAN SILT, PEBBLES
D
*2
AIR-LAID TUFF
REDDISH SOIL
AIR-LAID TUFF
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INTERLAYERED CINDER, SILT AND PEBBLES
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AIR-LAID TUFF
REDDISH SOIL
BOULDER LENS
REDDISH SOIL
AIR-LAID TUFF
REDDISH BROWN SOIL
INTERLAYERED REDDISH
GRAVEL
CINDER AND
BUFF SILT
OCHRE CINDER
DARK
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MASSIVE AA
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FIG. 3.

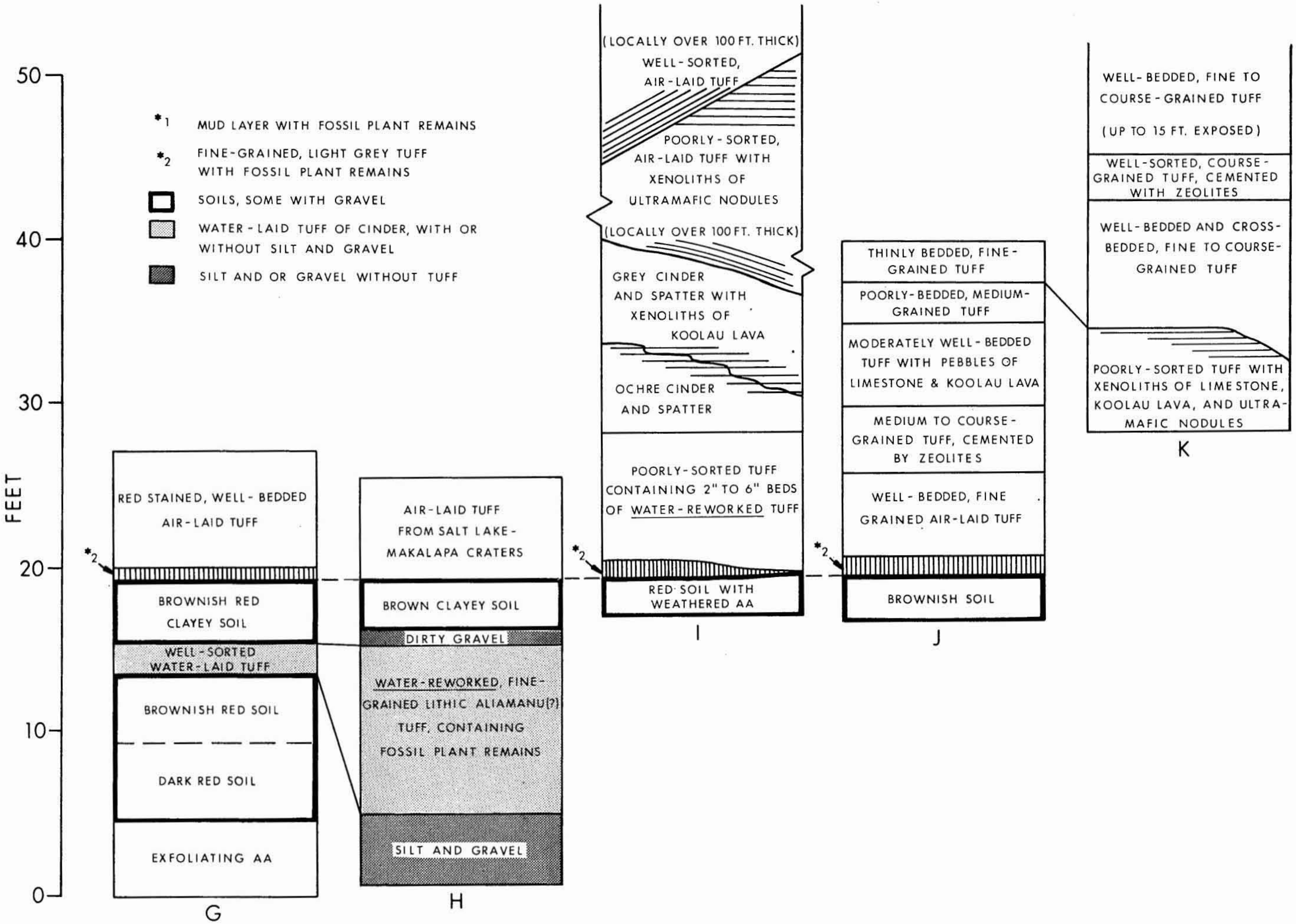


FIG. 3 (continued).

which grades farther downward into deeply weathered aa and pahoehoe flows of the Koolau Series.

A long series of terraces has been cut by the contractor for the Lakeside Subdivision to the south of Salt Lake, shown as location *W* on Fig. 1. In the westernmost part of this cut is found, with its base not exposed, a thickness of up to 16 feet of a rather poorly sorted and poorly bedded, palagonitized tuff rich in fragments of limestone and chunks of silt and mud. This section is unconformably overlain by the Salt Lake Tuff, here rather fine-grained and moderately well bedded. The Salt Lake Tuff itself is truncated and mantled by a loosely consolidated dark grey ash. The limestone-bearing tuff is also exposed along Salt Lake Boulevard north of the First Baptist Church. I consider it to be a remnant of a tuff cone, whose center was in the vicinity of the present Aliamanu School, and, therefore, refer to it as the Aliamanu School Cone. To the east, the contact between the Aliamanu School Tuff and the Salt Lake Tuff dips below the level of the ground. Farther east, the base of the Salt Lake Tuff becomes exposed in contact with a reddish brown soil. Here the bottom layer of the tuff is the light grey, loosely consolidated, plant-remains-bearing rock type that was noted on the hill north of the lake, at location *N*. Near the eastern end of this cut, the Salt Lake Tuff is truncated and mantled by the dark grey ash. In back of the parking lot of the apartment building at 3019 Ala Ilima (Polynesian Vista Apartments), location $W_1$ on Fig. 1, the ash mantle has been scalloped out by erosion and filled with a breccia consisting of angular fragments of reef material as well as pieces of tuff. These limestone blocks may be derived from the reef which caps the Salt Lake Tuff south of here (see location *V* on Fig. 1).

Several borings were made by the Dames and Moore Company in the lot prior to the construction of the apartment building called the Ala Ilima at 2907 Ala Ilima (locaton $W_2$ on Fig. 1). Mr. Song of the Dames and Moore Company noted (personal communication) that the tuff at the surface is about 8 feet thick; underlain by 3 to 10 feet of clays and silts; then by 3 feet of gravel, locally underlain by about 2 feet of tuff; then by 10 to 15 feet of clays and silts; then about 12 feet of another tuff, locally underlain by about 2 feet of tuffaceous sand; and then by an undetermined thickness of clays and silts. On the basis of this description, correlation of this section with any exposed in actual cuts is extremely tenuous. The low tuffaceous sand may perhaps be equivalent to the water-laid cinder and the intermediate tuffs intercalated with gravel may be derived from the Moanalua or the Alaimanu School cones.

Southwest of the lake, in the back of the house at 3457 Ala Akulikuli just south of Ala Hinalo (shown as location *T* on Fig. 1) is exposed a small part of another local center of eruption, here referred to as the Akulikuli Vent, which predated the main eruption of Salt Lake Crater. This is composed of an irregularly shaped mass in two dimensions, extending to 10 feet above ground level and 8 feet wide at the base and with the third dimension being unclear, of medium grey, poorly bedded, and poorly sorted lava balls, ranging in diameter from several millimeters to about 20 cm. These balls are cemented by zeolites and calcite, and resemble sugar-dipped candy. The lava ball deposit is truncated by a strongly palagonitized, moderately well-bedded tuff derived from Salt Lake Crater. To the south on Ala Akulikuli, this tuff truncates another very similar tuff, possibly derived from an earlier eruption from Salt Lake Crater, but also possibly from another crater now completely mantled by later eruptions. An even more impressive truncation between these two tuffs is in back of the house at 3411 Ala Hinalo, at the corner of Ala Akulikuli, just 50 feet north of the lava ball deposit.

The large semicircular cut to the east of Salt Lake, shown as location *S* on Fig. 1, now scheduled to be the site of a high school, shows several episodes in the eruptive history of Salt Lake Crater. Near the south part of the cut is a hairline-sharp unconformity between two identical tuffs, with the lower tuff dipping north, and the upper tuff dipping south. Continuing to the north, the lower tuff gradually assumes a dip of 60° to the northeast, suggesting postdepositional deformation. This tuff is then mantled by the dark grey Salt Lake ash, which has been described previously. Fossil roots, some extending for over 6 feet along bedding planes, are abundant in the upper part of the ash in this location. Several good unconformable contacts between palagonitized tuff below and dark grey ash above are exposed in a series of cuts between Ala Puumalu and Ala Napunani, north of the high school site.

Aliamanu Crater is used at the present time as an ammunition storage reserve by the U.S. Army. This crater was considered by Stearns (Stearns and Vaksvik, 1935, p. 109) as the source of the dark grey cinder underlying the Salt Lake Tuff, the best exposure of which is in the cut at the corner of Puuloa Road and Moanalua Highway (location *D* in Fig. 1). However, there is no proof that some of the cinder could not have been contributed by eruptions from other now-completely-mantled vents in the Salt Lake area, or even from vents higher on the slopes of the Koolau ridges. Similar but considerably coarser cinder is exposed along the north rim road within the Aliamanu Military Reservation between storage areas no. 3 and no. 4, shown as location $I_1$ on Fig. 1. This particular cut is directly in line with the crest of the Koolau spur which extends seaward from Red Hill. The thin water-worked tuff beds near the base of this cut closely resemble layers intercalated with the red soil at Red Hill, as shown in *G* in Fig. 3. Two tuffs are mapped above the cinder deposit in Aliamanu Crater. Though basically very similar in composition and texture, the lower tuff can commonly be distinguished from the upper one. Characteristics of the older tuff are a lack of well-developed stratification and of sorting and an abundance of angular xenoliths of Koolau lithology. Characteristic of the upper tuff is a locally developed excellent stratification in the finer grained layers, with the bedding planes clearly outlined by stringers of coarser grained xenoliths of Koolau rock which are more resistant to erosion than the fine-grained tuff matrix. The imposing cliffs on the north side of Aliamanu Crater, including Puu Leilono, the highest peak, with an elevation of 485 feet above sea level, are composed of the lower tuff. The entire south and west rims of the crater are covered by the younger tuff. Prominent angular unconformities between the two tuffs are well exposed in the mouths of storage areas nos. 10, 11, 12, and 13 along the north rim road and nos. 1, 2, and 36 near the administration house on the east side of the crater. These locations are shown collectively as *I* on Fig. 1. The older tuff is probably derived from eruptions from Aliamanu Crater, although possibly from Salt Lake Crater. The younger one can be traced continuously to Salt Lake Crater.

Just east of the prominent bend in Salt Lake Boulevard, west of Salt Lake, an amphitheater-like topographic feature suggests an old cone, breached on the southwest side, completely mantled by tuff from Salt Lake Crater. This feature, shown as location *R* in Fig. 1, is here called the Wiliki Cone, after the name of the street along its side. Stearns (Stearns and Vaksvik, 1935, p. 109) noted that the topography southwest of Aliamanu is suggestive of vents mantled by Salt Lake Tuff. This area is covered by private homes at this time, and thus such evidence is no longer present.

Makalapa Crater is topographically the lowest, least prominent of the large craters of the Salt Lake group. Along Kamehameha Highway, between Halawa Gate in the north to just south of Makalapa Gate in the south, shown as location *K* on Fig. 1, are exposed interlayered very fine-grained and medium- to coarse-grained tuffs with xenoliths of Koolau lava and of coral reef and calcareous sandstone. The coarser tuffs are undoubtedly derived from Makalapa Crater, whereas the very fine-grained tuffs may be in part or entirely from Salt Lake Crater. Tuffs below these can be seen within the Pearl Harbor Naval Reservation, directly west of Kamehameha Highway, shown as location *J* on Fig. 1. Cuts *J* and *K* are shown in Fig. 3.

Tuffs from Salt Lake and from Makalapa Craters are overlain by calcareous sandstone, reef, and reef breccias in a number of exposures south and west of the craters. Good relationships can be seen at the following exposures:

1. In the back of the parking lot of the Polynesian Vista Apartments at 3019 Ala Ilima, just south of Salt Lake, location $W_1$ on Fig. 1;
2. Along the east shore of Waipio Peninsula, location $P_1$ on Fig. 1;
3. Along the west shore of the Submarine Base part of the Pearl Harbor Naval Reservation, location $P_2$ on Fig. 1;

4. Along the ditch parallel to Aolele Street, immediately north of the Honolulu International Airport, location *Q* on Fig. 1.

Exposure 1 has already been described. Exposures 2 and 3 face one another across the 1,500-foot-wide entrance to Pearl Harbor and are quite similar. Exposure 2 and others on Waipio Peninsula figure prominently in discussions of the age of the Salt Lake Tuff.

Stearns (Stearns and Vaksvik, 1935, p. 49–50) described a location near the south tip of Waipio Peninsula as follows: ". . . four feet of laminated (air laid) Salt Lake tuff full of molds of stems and branches of small trees rests on 4 to 12 inches of red soil overlying reef limestone . . . about 100 feet to the south along the coast line the tuff passes beneath sea level, still resting on the soil and containing tree molds . . . . The tuff at this point is overlain by six feet of emerged reef . . . thin seams of soft white lime, a fraction of an inch to an inch thick [are present] in the tuff . . . these seams [are of] secondary caliche . . . ."

Exposures in the ditches along Aolele Street, near the Honolulu International Airport, location *Q* on Fig. 1, contain an almost identical section. At the base is up to 2 feet of brown soil containing decomposing fragments of reef material. This is overlain by up to 5 feet of fine-grained, pisolite-bearing, air-laid tuff, containing upright tree trunks now replaced by limestone. The upper 2 to 3 feet of the tuff is interlayered with, and also crosscut by, stringers of very fine-grained, pinkish buff, faintly banded limestone, which very prominently crosscut the tree stems. This clearly demonstrates the limestone to be secondary, formed after the deposition of the tuff. The tuff and tree trunks are unconformably overlain by reef and reef breccia. The bands of limestone, which correspond to the caliche described by Stearns, also are found cutting the reef above the tuff.

Another cut in a bluff on the west side of Waikele Peninsula, one-half mile south of the Waipahu Railroad Depot, now just south of the Waipahu dump, is described by Stearns (Stearns and Vaksvik, 1935, p. 53) as follows:

1. Brown clayey marine silt of uniform texture and without apparent bedding—about 15 feet thick; 2. overlain by a brown soil filled with root casts of limonite—1/2 foot thick; 3. overlain by a bed of fossil oyster shells—1.2 feet thick; 4. overlain by a brown clayey silt without apparent bedding—0.3 foot thick; 5. overlain by a compact limestone in a single massive bed containing fossil shells, pebbles and numerous well-rounded calcareous sand grains arranged in crude laminae—5.7 feet thick; 6. overlain by a *hard brownish black carbonaceous layer containing a few calcareous sand grains* [italics by Pankiwskyj]—0.4 feet thick; 7. overlain by friable limestone consisting of sand grains and a few fossil shells and containing numerous root casts—2.5 feet thick; 8. overlain by friable brown clayey silt containing gravel and fossil shells at the bottom—more than 4 feet thick.

The dark carbonaceous layer, number 6 above, is described as a shallow lagoonal deposit. Stearns also expresses the opinion that the limestone beneath the carbonaceous layer was not far separated in time from the limestone above the layer. Ruhe, Williams, and Hill (1965, p. 493) state that this black layer, collected from a different outcrop than the one described by Stearns, is similar to the Salt Lake Tuff in X-ray diffraction pattern and in thin section. They further continue that since this layer is "interbedded" with limestones which Stearns recognized as belonging to the Waimanalo stand, the Salt Lake Tuff "must be younger than Waipio and at least as young as Waimanalo." Hay and Iijima (1966, p. 367) concur that this layer, which they refer to as a bentonitic claystone, is probably correlative with the Salt Lake Tuff, and that it is "interbedded" with limestone and oyster-shell deposits. However, they draw no conclusion as to the age of the tuff from this evidence. Moreover, they claim that the Salt Lake Tuff was not only deposited, but also palagonitized and cemented, with zeolites before the sea rose to the Waimanalo stand on the basis of "coraline limestone with rounded and angular fragments of zeolitic palagonite tuff lying at elevations of 15 to 20 feet near the foot of a wave-cut cliff of similar zeolitic palagonite tuff [in the vicinity of location *V* on Fig. 1 of this paper].

I visited the Waipahu dump site, possibly the same cut examined by Ruhe et al. (1965), and found that the one-half-foot dark layer sandwiched between the two limestone beds contains numerous calcareous sand grains as well as rounded fragments up to 1/8 inch in size, and also that it is rich in fragments of plant casts in random orientations. There is a pronounced lamination in the rock due to alternating bands of dark "tuffaceous" material with bands rich in calcareous sand. It would thus appear that the layer in question is an interbedded mixture of detrital calcareous sand, a silt which is tuffaceous, at least in part, and fossilized plant fragments which were possibly washed in rather than growing *in situ*. The tuffaceous material may be original infall from an eruption in the Salt Lake area. On the other hand, it may be reworked tuff, just as the calcareous sand in which it is interbedded is reworked reef. In this case it would imply that this tuffaceous layer was reworked in Waimanalo time (provided that the underlying and overlying limestones are of Waimanalo age) and not that the Salt Lake craters were still erupting in Waimanalo time.

### *Mineralogy and Petrology*

The tuffs of the Salt Lake area are composed of particles from several origins: juvenile pyroclastic particles belonging to the Salt Lake Phase of the Honolulu Volcanic Series; fragments of a melilite-nephelinite lava erupted from one or more of the Salt Lake craters; xenoliths of medium- to coarse-grained ultramafic material; and xenoclasts derived from underlying coral reef, sediments, sedimentary rocks, and the Koolau Volcanic Series, as well as fragments of tuff from earlier eruptions of various craters in the Salt Lake area.

The juvenile pyroclastic particles are of varied mineralogy, primarily as a function of their degree of crystallinity. The amount of glass ranges from 95 percent to less than 25 percent. The glass ranges from perfectly fresh sideromelane, through palagonite, to a cryptocrystalline devitrite. In standard thickness thin section the color of the glass ranges from chestnut reddish brown or pale greyish green to practically opaque black. Alteration from the reddish brown to the pale greyish green has been observed in a number of thin sections, and it is the green that replaces the reddish brown. The opaque glass does not allow one to observe color changes due to alteration. However, in all grains alteration can be noted by the replacements of mineral grains and the filling of vesicles. In addition, two contrasting types of juvenile particles were observed, each of which I consider to have solidified at different depths. The shallower formed particles are composed of glass of any of the colors described above, containing various amounts of olivine and magnetite. Less abundant, if at all present, are crystals of melilite, needlelike clinopyroxene, and nepheline. The deeper formed particles contain fragments of a colorless to very pale green (in section) clinopyroxene ($2V_z = 60° \pm 1°$; $Z \wedge c = 44°$) showing a reaction zone and rimmed by a strongly zoned, honey-colored (in section) clinopyroxene ($2V_z = 65° \pm 2°$; $Z \wedge c = 54°$) with dispersion $r > v$. Other megacrysts present in the deeper formed particles are embayed blocky grains of olivine and smaller, more elongate grains of olivine which are not embayed. The groundmass is composed of fine-grained, needlelike clinopyroxene ($Z \wedge c = 54°$), altered melilite, and devitrified glass (?) filled with dust-size opaque material. The deeper formed particles were recognized to be such because their mineralogy is identical with that of the dark rims which are found around most of the ultramafic xenoliths present in the tuff, and also because they have been found forming cores rimmed by material of the shallower formed type. Fragments of xenoliths of Koolau Series lithology, coral reef, various sedimentary rocks, and of the melilite-nephelinite lava do not have such deeper formed rims.

Brief descriptions of the mineralogy and petrology of the deposits in the Salt Lake area were made by Dana (1849), Hitchcock (1900), Stearns and Vaksvik (1935), and Winchell (1947). A more complete description was presented by Hay and Iijima (1968). I concur with the description of the Salt Lake Tuff as a lithic-vitric tuff of melilite-nephelinite composition containing considerable amounts of fragments of tholeiitic material (from the underlying Koolau volcanics), as well as other introduced particles.

Stearns (1940, p. 55) mentioned the discovery in a well sunk in Aliamanu Crater of a "thirty-one-foot thick dark grey dense nonporphypitic basalt" below Salt Lake Tuff and above alluvium resting on Koolau basalt. He feels that this lava erupted "at the close of the explosive phase in Aliamanu Crater." The petrographic description, by G. A. Macdonald, in this report states that

> . . . it is a melilite-nepheline basalt containing colorless microphenocrysts of olivine reaching 0.3 mm across. The groundmass consists of a network of subhedral grains of altered melilite, lath-shaped in cross section, and between them euhedral to subhedral grains of nepheline, anhedral grains of augite and olivine, equate grains of magnetite, and greenish-brown interstitial glass. Highly acicular crystals of apatite are abundant. . . .

I was not able to locate samples from this well, nor thin sections of these samples. However, numerous angular blocks within the Salt Lake Tuff, especially concentrated in the periphery of the lake, correspond exactly to this type of rock. A chemical analysis of one of these blocks was made for the writer at the laboratories of the U.S. Geological Survey at Menlo Park. This analysis, together with a CIPW norm and a thin section mode, are presented in Table 1.

TABLE 1

COMPOSITION OF "ALIAMANU BASALT" BY PERCENT

| | | |
|---|---|---|
| CHEMICAL ANALYSIS | | |
| $SiO_2$ | | 37.10 |
| $TiO_2$ | | 2.93 |
| $Al_2O_3$ | | 11.75 |
| $Fe_2O_3$ | | 6.39 |
| $Cr_2O_3$ | | 0.04 |
| FeO | | 9.14 |
| MgO | | 10.56 |
| CaO | | 11.48 |
| MnO | | 0.23 |
| $Na_2O$ | | 4.92 |
| $K_2O$ | | 1.61 |
| $H_2O+$ | | 1.22 |
| $H_2O-$ | | 0.91 |
| $P_2O_5$ | | 1.23 |
| $CO_2$ | | 0.04 |
| Cl | | 0.06 |
| F | | 0.09 |
| Total | | 99.70 |
| NORM (CIPW) | | |
| an | | 5.84 |
| ne | | 22.15 |
| lc | | 7.41 |
| di | wo | 12.41 |
| | en | 8.60 |
| | fs | 2.77 |
| ol | fo | 12.46 |
| | fa | 4.59 |
| cs | | 4.50 |
| mt | | 9.28 |
| il | | 3.65 |
| ap | | 2.69 |
| MODE (FROM THIN SECTION) | | |
| Nepheline | | 70 |
| Melilite | | 15 |
| Clinopyroxene | | 6 |
| Glass | | 4 |
| Magnetite | | 3 |
| Olivine | | 1.5 |
| Apatite | | 0.5 |

*Ages of the Rocks in the Salt Lake Area*

Eruptions during the Pleistocene epoch in the Salt Lake area span times of sea level considerably higher than at present, followed by other levels considerably lower than the present, and finally one level about 25 feet higher than the present. These have been correlated by Stearns (in Stearns and Vaksvik, 1935, p. 127–128) respectively with the Kaena, Waipio, and Waimanalo stands of the sea about the island of Oahu. On a worldwide scale, these three are correlated in time respectively with the Yarmouth Interglacial, the Illinoian Glacial, and the Sangamon Interglacial (Stearns, 1966, p. 23). The dates of these are still a matter of contention. One time scale, by Ericson, Ewing, and Wollin (1964, p. 731) gives the end of the Yarmouth at 420,000 years B.P., the end of the Illinoian at about 340,000 B.P., and the end of the Sangamon at about 120,000 years B.P.

Blocks of fresh melilite nephelinite collected in the Salt Lake Tuff yielded a $K_{40}/A_{40}$ age of 430 ± 25, 446 ± 2, 418 ± 18 thousand years in three separate runs (Gramlich, Lewis, and Naughton, 1971). If this rock can be correlated with the 31-foot-thick flow at the base of the Salt Lake Tuff below the present-day bottom of Aliamanu Crater (Stearns, 1940, p. 55), this dates the period of eruption in Aliamanu Crater, from which the water-laid cinder below the Salt Lake Tuff may be derived. The water reworking of the cinder attests to a higher level of the sea than at present, and the 400,000 to

467,000 year age places this comfortably during the period of the Yarmouth Interglacial, as estimated by Ericson et al. (1964).

Coral reef terraces rising to the Waimanalo level have been dated by $Th_{230}/U_{238}$ methods. Four samples from Oahu from near Nanakuli, Kailua, Kahuku, and Haleiwa gave ages of respectively 120 ± 30, 110 ± 20, 110 ± 20, and 140 ± 30 thousand years (Veeh, 1966, p. 3383). The calcareous sandstone capping Salt Lake Tuff is correlated with the Waimanalo stand of the sea. Thus the date for the youngest eruptions from Salt Lake Crater predates 90,000 to 170,000 years B.P.

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